

BARYONIC DARK MATTER

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Reasons supporting the idea that most of the dark matter in galaxies and clusters of galaxies is baryonic are discussed. Moreover, it is argued that most of the dark matter in galactic halos should be in the form of MACHOs and cold molecular clouds.

One of the most important problems in modern astrophysics concerns the nature of the dark matter that pervades the Universe. In the following, we discuss several reasons that lead us to believe that most of the dark matter in galaxies and clusters of galaxies should be baryonic. Obviously, galaxy formation remains an open problem in this view, and the only explanation to date requires non-baryonic dark matter. Still, the point we want to make is that many properties of galaxies and clusters of galaxies are naturally accounted for by baryonic dark matter alone.

MACHOs and molecular clouds. From the standard Big Bang nucleosynthesis model one infers that $0.01 \leq \Omega_B \leq 0.1$. Since for the amount of luminous baryons one finds $\Omega_{\text{lum}} \ll \Omega_B$, it follows that an important fraction of baryons are dark and they may well make up the entire dark matter in galactic halos. Brown dwarfs and cold molecular clouds are probably the best candidates for dark matter in galaxies. Recent observations of microlensing events towards the Large Magellanic Clouds (LMC) suggest that MACHOs provide a substantial amount of the halo dark matter. Assuming a standard spherical halo model it has been found that the 8 microlensing events found so far¹ imply a halo MACHO fraction as high as 50% and an average mass of $0.27 M_\odot$ ². However, we note that the statistics of these events is at present too low to infer any definite conclusion since both the halo fraction in the form of MACHOs and their average mass strongly depend on the assumed model for the visible and dark matter components of the galaxy³.

The problem arises of how MACHOs formed and in what form the remaining fraction of the galactic dark matter is. A scenario in which dark clusters of MACHOs and cold molecular clouds naturally form in the halo at large galactocentric distances has been proposed as well as several methods to test this model^{4,5,6}. Basically, here the dynamics of the formation of dark clusters is similar to that of stellar globular clusters, the only difference being the larger galactocentric distance of dark clusters and consequently the lower incoming UV flux (from a central source). This fact implies that molecular hydrogen in dark clusters is not dissociated so that the Jeans mass can naturally reach values as low as $\sim 10^{-2} - 10^{-1} M_\odot$, leading to the

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formation of MACHOs. We note that also molecular clouds should form in dark clusters, since the process leading to MACHO formation does not have a 100% efficiency and the gas cannot be expelled due to the absence of strong stellar winds.

Very recently, a faint optical and near-infrared emission from the halo around the galaxy NGC5907 has been detected⁷, which is distributed in a manner that follows the expected distribution of the gravitational mass and provides the first direct indication that very faint stars with mass $\sim 0.1 M_{\odot}$ might be the repository of most of the dark matter in the halo of galaxies.

Dark matter at the centre of galaxies. Let us first assume that neutrinos make up the dark matter in galactic halos. The requirement that the maximum phase-space density does not violate the Pauli exclusion principle leads to the following lower limit for the neutrino mass⁸:

$$m_{\nu} \geq 120 \text{ eV} \left(\frac{100 \text{ km s}^{-1}}{\sigma} \right)^{1/4} \left(\frac{1 \text{ kpc}}{r_c} \right)^{1/2} g_{\nu}^{-1/4}, \quad (1)$$

where g_{ν} is the number of neutrino helicity states. For spiral galaxies ($\sigma \sim 150 \text{ km s}^{-1}$, $r_c \sim 10 \text{ kpc}$) one gets $m_{\nu} \geq 25 \text{ eV}$; for bright elliptical galaxies one gets $m_{\nu} \geq 5 - 7 \text{ eV}$. However, when considering dwarf galaxies ($\sigma \sim 20 \text{ km s}^{-1}$ and $r_c \sim 1 \text{ kpc}$) one gets $m_{\nu} \geq 200 \text{ eV}$, which is clearly in contradiction with the cosmological bound.

As next we consider cold dark matter as a candidate for the dark matter in galactic halos. In this respect, several computer simulations of the large scale structure with a sufficiently high resolution to resolve the internal structure of the galactic halos, seem to indicate that the density profiles of the cold dark matter should have central cusps. These cusps are incompatible with the isothermal density profiles $\rho(r) = \rho(0)/[1 + (r/r_c)^2]$. While this profile becomes approximately constant at $r \ll a$ and has a finite central density $\rho(0)$, numerical simulations⁹ indicate a density distribution that diverges like r^{-1} . The existence of a central density cusp in normal galaxies is difficult to demonstrate since the internal regions are gravitationally dominated by the visible component. On the contrary, dwarf spiral galaxies provide excellent probes for the internal structure of dark halos since these galaxies are completely dominated by dark matter on scales larger than a kiloparsec¹⁰. One can, therefore, use these galaxies to investigate the inner structure of dark halos with very little ambiguity about the contribution from the luminous matter and the resulting uncertainties in the disk mass/luminosity ratio (M/L). Only about a dozen rotation curves of dwarf galaxies have been measured, but a trend clearly emerges: the rotational velocities rise over most of the observed region, which spans several times the optical scale lengths and nevertheless lies within the core radius of the mass distribution. Rotation curves of dwarf galaxies do not admit singular density profiles at the galactic centre and their profiles are in good agreement with the isothermal density law. Given the above considerations, we conclude that the dark matter in dwarf galaxies has to be mainly baryonic and therefore, it is very likely that also in ellipticals and spirals it should be baryonic as well.

Galactic evolution along the Hubble sequence. It has been pointed out¹¹ that spiral galaxies evolve along the Hubble sequence from S_d to S_a in billions of years. During this evolution the dimensions of both galactic nuclei and disks

increase while the M/L ratio should decrease. This fact suggests that dark matter gradually transforms into visible matter, that is in stars. Of course, this is possible only if the dark matter is baryonic and, in particular, if it is in gaseous form.

Rotation curve shapes. Initial studies have indicated that rotation curves of spiral galaxies are generally flat. This means that the galactic halo must produce practically the entire rotational velocity far out the optical radius, while in the internal regions the optical disk maximally contributes to the rotation curve. It seems that disk and halo combine together to produce a flat rotation curve. This synthyony between disk and halo has been called the *disk-halo conspiracy*. However, this *conspiracy* is not always true. In some dwarf galaxies the dark halo mass is considerably higher than the luminous disk mass inside the optical radius. In the internal regions of bright spirals the disk is the dominant component, while the halo contributes significantly to the rotation curve only at large galactocentric distances¹². The dependence of the rotation curves on the luminous content of the spiral galaxies, we are talking about, can be explained if the dark matter in spirals is baryonic and in particular if halos formed before galactic disks, as it naturally happens in our model⁵.

Dark matter in clusters of galaxies. It is well known that the ratio M/L increases from the luminous part of galaxies to clusters and superclusters of galaxies. This fact has generally induced astrophysicists to conclude that clusters and superclusters of galaxies have much more matter per unit luminous matter than individual galaxies, so that the critical density of the Universe can be attained. Recently, it has been shown¹³ that most of the dark matter in clusters and superclusters of galaxies should be clumped in the halos around galaxies. Indeed, the ratio M/L in clusters does not significantly increase at scales larger than 100–200 kpc, typical of galactic halos. The total mass of the clusters can then be accounted for by the mass of the galaxies plus the hot gas mass ($\sim 20\%$ of the total cluster mass). This, in addition to the fact that the voids seem to give a minor contribution to Ω , suggests that Ω can be as low as ~ 0.2 .

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